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This program supported the visit of Professor V. F. Nesterenko, Lavrentiev Institute of Hydrodynamics, Novosibirsk, Russia to UCSD, La Jolla, CA. Associated research focused on shock- and shear-initiated chemical reactions and the use of the thick-walled cylinder method for the generation of high shears at high strain rates. The program was successfully completed with the firm establishment of collaborative research and opening of new research areas.		15. NUMBER OF PAGES	
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A FUNDAMENTAL INVESTIGATION OF SHOCK-INDUCED REACTIONS:  
THE ROLE OF PLASTIC DEFORMATION AND SYNTHESIS  
OF ULTRA HARD MATERIALS

FINAL TECHNICAL REPORT

MARC ANDRE MEYERS  
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The research program was successfully completed and all objectives in the original proposal were accomplished. Dr. Nesterenko's stay at UCSD was extended and culminated with the offer for a position of Associate Professor in Residence, that he accepted. He was promoted to Full Professor (with tenure) in July 1998. The research program resulted in the publication of a considerable number of papers, that have already been submitted to the US Army Research Office. The following are the main accomplishments of the program:

1. It was demonstrated that intense plastic deformation occurring in shear localization can lead to exothermic chemical reactions in the Nb-Si and Ti-Si systems.
2. It was shown that shear localization can be observed in tantalum under extreme conditions of loading, which are experienced in the thick-walled tube geometry.
3. Damage evolution under dynamic deformation was investigated in alumina and silicon carbide. An in-depth analysis of ceramic comminution under impact conditions was carried out.
4. The self-organization of shear bands in titanium was demonstrated and quantified. This work was done in collaboration with Dr. T. W. Wright, u. S. Army research Laboratory.
5. Prof. Nesterenko is completing his book; it is expected to be published by Springer in 2001.

A list of papers published as a result of this research program and interactions after its conclusion is given below. The papers listed resulted from work in this program and subsequent work initiated during the visit of Prof. Nesterenko.

1. V.F. Nesterenko, M.A. Meyers, H.C. Chen, and J.C. LaSalvia, "Controlled High-Rate Localized Shear in Porous Reactive Media", *Applied Physics Letters*, December 12, 1994, vol. 65, (no. 24), p. 3069-3071. RESEARCH ARTICLE
2. V.F. Nesterenko, M.A. Meyers, C.H. Chen, and J. LaSalvia, "The Structure of Controlled Shear Bands in Dynamically Deformed Reactive Mixtures", *Metallurgical and Materials Transactions A*, 1995, vol. 26A, October, p. 2511-2519. RESEARCH ARTICLE
3. V.F. Nesterenko, M.A. Meyers, and H.C. Chen, "Shear Localization in High-Strain-Rate Deformation of Granular Alumina", *Acta materialia*, 1996, vol. 44, (no. 5), p. 2017- 2026. RESEARCH ARTICLE
4. V.F. Nesterenko, "Dynamic Loading of Porous Materials: Potential and Restrictions for Novel Materials Applications", in *Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena* Proceedings of the 1995 International Conference EXPLOMET-95, El Paso, August 6-10, Editors L.E. Murr, K.P. Staudhammer, and M.A. Meyers, Elsevier Science B.V., 1995, pp. 3-13. CONF PROCEED
5. V.F. Nesterenko, M. A. Meyers, and T.W. Wright, CONF

"Collective Behavior of Shear Bands" in Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena, Proceedings of the 1995 International Conference EXPLOMET-95, El Paso, August 6-10, Editors L.E. Murr, K.P. Staudhammer, and M.A. Meyers, Elsevier Science B.V., 1995, pp. 397-404. PROCEED

6. M.A. Meyers, V.F. Nesterenko, Y.J. Chen, J.C. LaSalvia, M.P. Bondar, and Y.L. Lukyanov, "High-Strain, High-Strain-Rate Deformation of Tantalum: the Thick-Walled Cylinder Method", in Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena, Proceedings of the 1995 International Conference EXPLOMET-95, El Paso, August 6-10, Editors L.E. Murr, K.P. Staudhammer, and M.A. Meyers, Elsevier Science B.V., 1995, pp. 487-494. CONF PROCEED

7. H.C. Chen, M.A. Meyers, and V.F. Nesterenko, "Chemical Reaction in Ti-Si Mixture under Controlled High-Strain-Rate Plastic Deformation", in Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena, Proceedings of the 1995 International Conference EXPLOMET-95, El Paso, August 6-10, Editors L.E. Murr, K.P. Staudhammer, and M.A. Meyers, Elsevier Science B.V., 1995, pp. 723-729. CONF PROCEED

8. H.C. Chen, M.A. Meyers, and V.F. Nesterenko, "Shear Localization in Granular and Commuted Alumina", in SHOCK COMPRESSION OF CONDENSED MATTER - 1995, Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter, Seattle, August 13-18, 1995, AIP Press, 1996, Edited by S.C. Schmidt and W.C. Tao, p.607-610. CONF PROCEED

9. V.F. Nesterenko, M.A. Meyers, Y.J. Chen, and J.C. LaSalvia, "Chemical Reactions in Controlled High-Strain-Rate Shear Bands", in SHOCK COMPRESSION OF CONDENSED MATTER - 1995, Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter, Seattle, August 13-18, 1995, AIP Press, 1996, Edited by S.C. Schmidt and W.C. Tao, p.713-716. CONF PROCEED

10. D.J. Benson, V.F. Nesterenko, and F. Jonsdottir, "Micromechanics of Shock Deformation of Granular Materials", in SHOCK COMPRESSION OF CONDENSED MATTER - 1995, Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of CONF PROCEED

Condensed Matter, Seattle, August 13-18,  
1995, AIP Press, 1996, Edited by S.C. Schmidt  
and W.C. Tao, p.603-606.

11. D.J. Benson, V.F. Nesterenko, and F. Jonsdottir, CONF  
"Numerical Simulations of Dynamic Compaction", PROCEED  
Net Shape Processing of Powder Materials,  
AMD-Vol. 216, Edited by S. Krishnaswami,  
R.M. McMeeking, and J.R.L. Trasorras, ASME, NY,  
1995, pp. 1-8.

12. J.LaSalvia, Y.J.Chen, M.A.Meyers, V.F.Nester- CONF  
enko, M.P. Bondar, and Y.L. Lukyanov, "High- PROCEED  
Strain, High-Strain-Rate Response of Annealed and Shocked  
Tantalum", Edited by E. Chen, A. Crowson, E. Lavernia,  
W. Ebihara, P.Kumar, The Minerals, Metals & Materials Society,  
1996, pp. 139-144.

13. V.F. Nesterenko, M.A. Meyers, and T. W. Wright, CONF  
"Characteristic Spacing in a System of Adiabatic PROCEED  
Shear Bands", Proceedings of Plasticity' 97: The Sixth  
International Symposium on Plasticity and its Current Applications,  
Edited by Akhtar S. Khan, Juneau, Alaska, July 14-18,  
1997, pp.131-132.

14. S.R. Cooper, D.J. Benson, and V.F. Nesterenko, CONF  
"The Role of Void Geometry on Hot Spot PROCEED  
Formationin Ductile Materials", Proceedings of Plasticity' 97:  
The Sixth International Symposium on Plasticity and its Current  
Applications, Edited by Akhtar S. Khan, Juneau, Alaska, July 14-18,  
1997, pp.301- 302.

15. V.F. Nesterenko, M.A. Meyers, and T.W. Wright, RESEARCH  
"Self- Organization in the Initiation of Adiabatic ARTICLE  
Shear Bands" (previous title"Self-Organization  
of Shear Bands in High-Strain-Rate Deformation",  
Acta materialia, 1998, vol.46, no. 1, pp. 327-340.

16. D.J. Benson, V.F. Nesterenko, F. Jonsdottir, and RESEARCH  
M.A. Meyers, "Quasistatic and Dynamic Regimes ARTICLE  
of Granular Material Deformation under Impulse Loading", Journal of  
the Mechanics and Physics of Solids, 1997, vol.45,  
no. 11/12, pp. 1955-1999.

17. C.J. Shih, V.F. Nesterenko, and M.A. Meyers, CONF  
"Shear Localization and Comminution of Granular PROCEED  
and Fragmented Silicon Carbide", JOURNAL DE PHYSIQUE IV, Colloque  
C3, supplement au Journal de Physique III, n. 7, 1997, vol. 7, p. C3-  
577-C3-582.

18. H.C. Chen, V.F. Nesterenko, J.C. LaSalvia, and CONF  
M.A. Meyers, "Shear-Induced Exothermic PROCEED  
Chemical Reactions", JOURNAL DE PHYSIQUE IV, Colloque C3,  
supplement au Journal de Physique III, n. 7, 1997, vol. 7, p. C3-27 -  
C3-32.

19. Y.J. Chen, J.C. LaSalvia, V.F. Nesterenko, M.A. Meyers, M.P. Bondar, and Y.L. Lukyanov, "High-Strain, High-Strain-Rate Deformation, Shear Localization and Recrystallization in Tantalum", JOURNAL DE PHYSIQUE IV, Colloque C3 supplement au Journal de Physique III, n. 7, 1997, vol.7, p. C3-435 -C3-440. CONF PROCEED

20. M.A. Meyers, J.C. LaSalvia, V.F. Nesterenko, and B.K. Kad, "Dynamic Recrystallization in High-Strain-Rate Deformation", Proceedings of REX 96, the Third International Conference on Recrystallization and Related Phenomena, Edited by Terry R. McNelley, Monterey, CA, 1997, p. 279 - 286. CONF PROCEED

21. V. F. Nesterenko, M.A. Meyers, J. LaSalvia, M.P. Bondar, Y.J. Chen, and, Y.L. Lukyanov "Shear Localization and Recrystallization in High-Strain, High-Strain-Rate Deformation of Tantalum" (previous title "Investigation of High-strain, High-Strain-Rate Behavior of Tantalum Using the Collapse of a Thick-Walled Cylinder") Materials Science & Engineering, 1997, A229, p.23-41. RESEARCH ARTICLE

22. V.F. Nesterenko, "Controlled High-Rate-Strain Shear Bands in Inert and Reactant Porous Materials", in SHOCK COMPRESSION OF CONDENSED MATTER -1997, Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter, Amherst, 27 July - 1 August 1997, Edited by S.C. Schmidt, D.P. Dandekar, and J.W. Forbes, AIP Conference Proceedings 429, American Institute of Physics, Woodbury, New York, 1998, pp. 609-614. CONF PROCEED

23. C.J. Shih, V.F. Nesterenko, and M.A. Meyers, "High-Strain-Rate Deformation and Comminution of Silicon Carbide", J. Appl. Phys.. 1998, vol. 83, No.9, pp. 4660-4671. RESEARCH ARTICLE

24. H.C. Chen, J.C. LaSalvia, V.F. Nesterenko, and M.A. Meyers, "Shear Localization and Chemical Reaction in High-Strain, High-Strain-Rate Deformation of Ti-Si Powder Mixtures", Acta materialia, vol. 46, no.9, 1998, pp. 3033-3046. RESEARCH ARTICLE

25. H.C. Chen, V.F. Nesterenko, and M.A. Meyers, "Shear Localization and Chemical Reaction in Ti-Si and Nb-Si Powder Mixtures: Thermochemical Analysis", J. Appl. Phys., 1998, vol. 84, no.6, 15 Sept. pp. 3098-3106. RESEARCH ARTICLE

26. C.J. Shih, M.A. Meyers, and V.F. Nesterenko, "High-Strain-Rate Deformation of Granular Silicon Carbide", Acta materialia, 1998, vol.46, no.11, pp.4037-4065. RESEARCH ARTICLE

27. M.A. Meyers, V.F. Nesterenko, K.S. Vecchio, and S.S. Batsanov, "Shock and Shear Induced Chemical Reactions in Mo-Si, Nb-Si, and Ti-Si Systems", In CONF PROCEED

Molybdenum and Molybdenum Alloys, TMS, Editors A. Crowson, E.S. Chen, J.A. Shields, and P.R. Subramanian, 1998, pp. 221-239.

28. V. I. Levitas, V. F. Nesterenko and M. A. Meyers, "Strain-Induced Structural Changes and Chemical Reactions. Part I", *Acta materialia*, 1998, vol. 46, No. 16, pp. 5929-5945. RESEARCH ARTICLE

29. V. I. Levitas, V. F. Nesterenko and M. A. Meyers, "Strain-Induced Structural Changes and Chemical Reactions. Part II", *Acta materialia*, 1998, vol. 46, No. 16, pp. 5947-5963. RESEARCH ARTICLE

30. V. I. Levitas, V. F. Nesterenko and M. A. Meyers, "Strain-Induced Chemical Reactions in Shear Bands: Experiments and Modeling". *Constitutive and Damage Modeling of Inelastic Deformation and Phase Transformation, Proceedings of Plasticity'99, Cancun, Mexico 5-13, 1999*, pp. 243-246. CONF PROCEED

31. V. F. Nesterenko, Q. Xue, M. A. Meyers, and W. Wright "Dependence of Characteristic Spacings in a system of Adiabatic Shear Bands on Material Property". *Constitutive and Damage Modeling of Inelastic Deformation and Phase Transformation, Proceedings of Plasticity'99, Cancun, Mexico 5-13, 1999*, pp. 507-510. CONF PROCEED

32. Y.-J. Chen, M. A. Meyers and V. F. Nesterenko "Spontaneous and Forced Shear Localization in High-Strain-Rate Deformation of Tantalum". *Materials Science and Engineering A*, (in press). RESEARCH ARTICLE

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